

Observations of ^3He -rich Solar Energetic Particle Events with the Solar Isotope Spectrometer

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Abstract. Using ~ 4 MeV/nucleon solar energetic particle data from the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE), we identify 60 ^3He -rich time periods longer than 5 hours in length. As many of these time periods do not have "classical" impulsive profiles, we classify each event as one of 4 event types (based on the morphology of the event). The time periods have been associated with solar events listed by the Space Environment Center and energetic electron events observed by the Electron, Proton, and Alpha Monitor (EPAM) on ACE. Only half of the events could be associated with an x-ray event and 63% with an electron event.

1. Introduction

Solar energetic particle (SEP) events rich in ^3He were first observed by Hsieh & Simpson (1970). Since then numerous studies have been made in an attempt to understand the characteristics and origin of this type of event. Initially it was found that most of the observed ^3He -rich events could be identified with x-ray events with impulsive time profiles. Thus the terms "impulsive event" and " ^3He -rich event" became synonymous. Recently, evidence indicating the ^3He enrichments are not solely a property of impulsive events (Cohen et al. 1999; Mason, Mazur, & Dwyer 1999) has prompted discussion regarding distinctions to be made between the two terms. However, for the purpose of this paper we will use the phrases interchangeably.

While it was originally believed that impulsive events were relatively rare, it is now thought that $\gtrsim 1000$ such events per year occur on the visible solar disk (Reames, Meyer, & von Rosenvinge 1994). Most of our understanding of ^3He -rich events comes from studies by ISEE-3 from 1978 through 1991 (Mason et al. 1986; Reames, Meyer, & von Rosenvinge 1994; Reames et al. 1988; Reames, von Rosenvinge, & Lin 1985). These studies revealed that impulsive events

commonly have $^3\text{He}/^4\text{He}$ ratios as great as 2000 or more times that observed in the solar wind; they are associated with soft x-ray events and scatter-free electron events. Certain heavy ions are frequently enhanced, with the Ne-Si group relative to CNO being a factor of ~ 3 higher than typical in large "gradual" SEP events and Fe being a factor of ~ 10 higher.

While these studies have resulted in a detailed characterization of impulsive events, it is still not clear what causes the abundance patterns, which are quite different from those in gradual SEP events. The heavy ion enhancements, which are remarkably constant from event to event (Mason et al. 1986), are most likely a result of Q/M fractionation occurring in coronal material with a temperature of 3-5 MK (Reames et al. 1994). In this temperature range Ne-Si have similar Q/M values which differ substantially from those of CNO and that of Fe, thus Q/M fractionation could result in the observed enhancement pattern. In contrast, the ^3He enrichment varies substantially from event to event and the cause of this enhancement remains unclear. Properties of related x-ray events have been examined in an attempt to identify characteristics correlated with the degree of ^3He enrichment, but only a weak anti-correlation with soft x-ray peak flux was found, suggesting that ^3He enrichment preferentially occurs in smaller flares (Reames et al. 1988). It has been observed that impulsive events primarily originate from heliolongitudes west of ~ 20 degrees (Reames 1999).

The launch of the Advanced Composition Explorer (ACE) presents a new opportunity to study ^3He -rich events at high levels of sensitivity. One of the instruments on board is the Solar Isotope Spectrometer (SIS) (Stone et al. 1998), a dE/dx versus residual energy instrument consisting of two Si detector telescopes with a combined geometry factor of $\sim 40 \text{ cm}^2\text{-sr}$. Each telescope contains two position-sensing detectors which provide the angle of incidence of the incoming particle. These detectors are followed by a stack of 8 large-area detectors to measure the energy deposited by the particle. Using this information, the nuclear charge, mass, and kinetic energy can be determined for He - Ni at energies of ~ 5 to $\sim 100 \text{ MeV/nucleon}$. In this work we concentrate on He data obtained at the lower limit of the SIS energy range.

2. Data Analysis

The two isotopes of He can readily be identified in the SIS data. We have taken hourly averaged rates of ^3He and ^4He with 3.5 - 4.5 MeV/nucleon and computed a $^3\text{He}/^4\text{He}$ ratio. We then identified time periods of ≥ 5 hours in length where the $^3\text{He}/^4\text{He}$ ratio was ≥ 0.1 . Consecutive time intervals that were separated by only one hour were combined into one, resulting in 92 time periods. The ^3He and ^4He rates were examined for increases indicative of an event onset prior to or coincident with the identified ^3He -enrichment time period. Onsets were apparent in 60 of the events; it is this subset that is the subject of this study.

In previous studies, reasonable success was achieved using the observed velocity dispersion of electrons to determine the onset time of an event at the Sun (Reames et al. 1985). These onset times were then used to associate the particle event with an occurrence on the Sun - typically an x-ray event. We have examined the electron data from the Electron, Proton and Alpha Monitor (EPAM) on ACE in the energy range 38 - 53 keV (R. Gold, private communication, 2000)

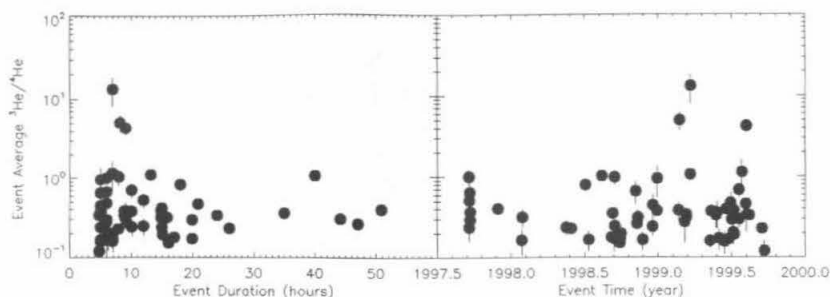


Figure 1. Average $^3\text{He}/^4\text{He}$ ratios as a function of event duration and time of occurrence for the 60 selected time periods.

for events occurring at times similar to the He onsets observed in the SIS data. We were able to identify 38 time periods with clearly defined electron events. No attempt was made to use velocity dispersion to refine the association of the electron event with candidate x-ray events.

A list of solar events was obtained from the U. S. Department of Commerce, NOAA, Space Environment Center and the onset times of x-ray events were compared to those of the 60 SIS He events. Assuming a path length of 1.2 AU (Reames et al. 1985), ions at 4 MeV/nucleon would take ~ 2 hours to reach ACE. A 4.8 hour window prior to the He onset was examined for x-ray events occurring in the western hemisphere. An additional criterion imposed was that the candidate x-ray event had to precede the electron event onset when one was apparent. It was possible to make an x-ray association for 29 of the 60 events, 23 of these also had an associated electron event.

3. Discussion

For each of the 60 periods selected a $^3\text{He}/^4\text{He}$ fluence ratio was determined. These values ranged from 0.12 to 13. Figure 1 shows the $^3\text{He}/^4\text{He}$ ratios plotted as a function of the length of the enrichment period as well as the time of occurrence. It is evident that the majority of the events are < 10 hours long, although some last the better part of 2 days or more. In general, there is no correlation between the length of the event and the average ^3He enrichment. The enrichment is also not strongly dependent on the time of occurrence of the event, although it is clear that the frequency of such events is increasing as the solar cycle approaches maximum.

Many of the selected enrichment periods do not occur during the main phase of the impulsive event. In some of the events the $^3\text{He}/^4\text{He}$ ratio does not exceed 0.1 until the decay phase of the event. While in some cases this is an artifact of our chosen threshold and the $^3\text{He}/^4\text{He}$ ratio is actually enhanced throughout the event (just not at the 0.1 level), there are other cases where the ^3He is increasing while the ^4He is decreasing or remaining constant. Our survey of 60 events reveal many which do not exhibit the "classic" impulsive event profile.

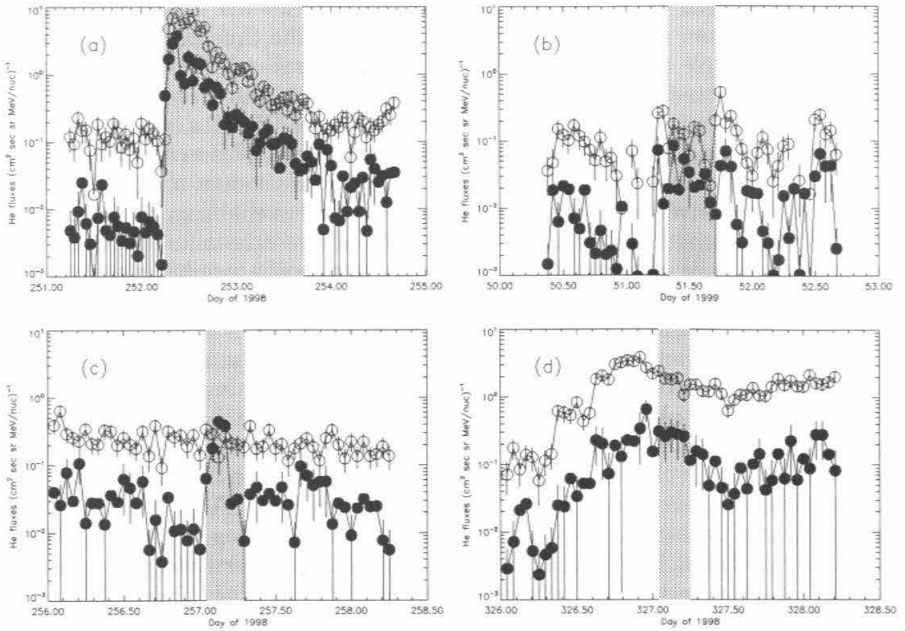


Figure 2. Examples of the 4 defined event types: (a) Classic, (b) Decay, (c) Independent and (d) Indeterminate. See text for explanation of each type. The shaded region denotes the selected ^3He enrichment period. The solid points are ^3He and the open points are ^4He .

We have categorized the events into 4 broad categories, examples of which are given in Figure 2.

The categories are (1) Classic, (2) Decay, (3) Independent and (4) Indeterminate. Classic events are those in which the ^3He enrichment occurs during the onset and peak of the event (and often continues throughout the decay phase). The ^3He and ^4He rate onsets are coincident (or nearly so) and typically very rapid. These are the “standard” types of events that have been previously studied. Decay events are those during which the $^3\text{He}/^4\text{He}$ ratio exceeds 0.1 after the peak of the event has occurred. In most cases, the two He rates track each other well, but the required threshold is not exceeded until later in the event, primarily due to a more rapid decrease in the ^4He rate. In other cases the ^3He statistics are limited, causing the ^3He rate to be quite variable and the threshold is not exceeded until the decay phase.

Independent events are ones where the behavior of the ^3He appears to be unrelated to that of the ^4He . Often there is a clear onset in the ^3He rate while the ^4He rate remains nearly constant or continues to decline from a previous event. Finally there were several events which were difficult to classify due to their uniqueness. This category includes events where a slight increase in the ^3He level (with no corresponding ^4He increase) causes the $^3\text{He}/^4\text{He}$ ratio to exceed 0.1, those where ^4He decreases slightly with no corresponding ^3He decrease, and

periods significantly lagging any apparent event onset such that it is uncertain if the enhancement and event onset were related. The time period in Figure 2 used as an example of the Indeterminate category has a very gradual event onset (not typical of classic impulsive events), where the ^3He and ^4He rates track each other well. The enhancement period occurs when the ^4He rate begins to decline while the ^3He rate remains constant. Although the $^3\text{He}/^4\text{He}$ ratio is enhanced over solar wind values during the entire event, this event does not fit the classic picture of impulsive events. It is possible that this event may be an example of a suggestion made by Mason et al. (1999) where remnant ^3He from prior impulsive events is accelerated by interplanetary shocks resulting in enhanced $^3\text{He}/^4\text{He}$ ratios in gradual events.

Reames et al. (1985) were able to identify increases in 10-100 keV electron data for all of their observed impulsive events. Looking at a more limited energy range (38-53 keV) we were able to identify clear electron increases in 38 of the 60 events. In a study of data from EPAM and the Ultra Low Energy Isotope Spectrometer (ULEIS) on ACE, Ho et al. (2000) identified 66 ^3He -rich events and were able to make a clear association with energetic electrons in only ~68% of the events, similar to the fraction we were able to correlate. The lower correlation between energetic electron and impulsive events found using the EPAM data in this study and that by Ho et al. may be due to the higher energy threshold of the EPAM data (as compared to that used by Reames et al. 1985).

Within each event category it was determined how many events could be associated with x-ray flares of different classes. The resulting statistics are given in Table 1 (along with the number of events with a clear electron increase for each category; the number in parentheses is the number of events with both an associated electron increase and x-ray event). While we restricted candidate x-ray events to those occurring on the west side of the Sun, some x-ray events did not have locations reported. These events are included in the table as the numbers following a "+" sign. Thus, "6+1" indicates 6 candidate events known to occur in the western hemisphere were identified along with 1 event of unknown location. It is evident from the x-ray data in Table 1 that impulsive events are predominantly associated with small flares (B- and C-class), consistent with the findings of Reames et al. (1988).

Table 1. Statistics for each defined event class

	Number	Elect.	X class	M class	C class	B class	No candid. x-ray
Classic	38	27 (17)	0+0	0+1	6+6	1+4	20
Decay	7	4 (3)	0+0	0+0	1+2	0+1	3
Independent	8	4 (1)	0+0	0+0	0+0	0+2	6
Indeterminate	7	3 (2)	0+1	0+1	0+1	0+2	2
Total	60	38	1	2	16	10	31

Reames et al. (1984) and Mason et al. (1986) examined heavy ion fluxes during impulsive events and found that there was no correlation between the size of the Fe and ^3He enhancements. There are enhancements of Fe apparent in

several of the events studied here, but since the majority of them had Fe fluxes that were dominated by galactic cosmic rays (GCRs) at SIS energies, it was not possible to correlate the Fe and ^3He enhancements. A more detailed study of heavy elements in 11 ^3He -rich events has been done by Slocum et al. (2000). The authors found that the heavy element content is similar to that which is typical of impulsive SEP events and no strong correlation between the Fe and ^3He enhancements was evident.

Events rich in ^3He have been well studied at energies of ~ 1 MeV/nucleon. With SIS data we have been able to observe these events at higher energies (~ 4 MeV/nucleon) and find that they exhibit many of the same characteristics. Of the 60 events studied, we find that a significant fraction (37%) do not have time profiles typical of the canonical impulsive event. We have defined 4 broad event type categories and suggest that more studies be made of the less conventional types. Half of the events could not be associated with an x-ray event on the western hemisphere of the Sun and in 37% we were unable to detect associated energetic electrons.

The fact that 92 periods of ≥ 5 hours in length were initially identified as having $^3\text{He}/^4\text{He}$ ratios > 0.1 out of ~ 780 days of data suggests that enhancements of ^3He are not a rare phenomenon. This observation is consistent with observations at lower energies by Mason et al. (1999) of significant enhancements of ^3He on a majority of days from November 1997 through June 1999. This remnant material (presumably from impulsive events) may be preferentially accelerated by the interplanetary shocks which produce the solar energetic particles observed in large, gradual events (Mason et al. 1999). Such a scenario could explain the unexpected observed enhancements of ^3He during several large gradual events observed by ACE over the last 3 years. It is possible that some of the enhancements observed here could also result from this mechanism.

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